AU/ACSC/2763/2008-09

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

THE NOSE KNOWS: DEVELOPING ADVANCED CHEMICAL SENSORS FOR THE REMOTE DETECTION OF IMPROVISED EXPLOSIVE DEVICES IN 2030

by

Julie V. Guill, Major, USAF

A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

Advisor: Colonel Zoe Hale

Maxwell Air Force Base, Alabama

April 2009

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **APR 2009**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **The Nose Knows: Developing Advanced Chemical Sensors for the Remote Detection of Improvised Explosive Devices in 2030**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Command And Staff College Air University Maxwell Air Force Base, Alabama**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		

14. ABSTRACT

Explosive detection sensor micro unmanned aerial vehicles (UAVs) equipped to identify the presence of improvised explosive devices (IEDs) and communicate their locations to commanders will significantly decrease military and civilian casualties in an unconventional warfare environment of 2030. The forecasting methods used for this paper are environmental scanning and genius. The Department of Homeland Security is encouraging research in Low Vapor Pressure Chemical Detection System (LVPCDS) programs to develop, field-test, and transition systems required to effectively detect high explosive residues and toxic low vapor pressure compounds. The LVPCDS program will assist DHS goals of developing enhancements to existing detection components and systems, developing new components and systems, as well as creating next generation systems. Proposed short range systems will be fully autonomous, portable and able to rapidly detect low vapor pressure chemicals from 3 meters or less without contacting the contaminated surface. ICx Nomadics Inc and GE have both demonstrated with their differing technologies that TNT can be detected in the vapor phase from a standoff distance of between 1 to 3 meters using sensors with sensitivity in the parts per trillion ranges. In order to detect low vapor pressure agents at the same distance as TNT can be detected currently, sensors may require sensitivity to the parts per quadrillion to quintillion (10.0 E 12- 10.0 E 15) ranges. With this capability, sensors may be able to detect TNT from a standoff distance of 6-9 meters. A realistic vision of a 20-year future has fielded U.S. forces able to see a complete picture in their normal field of view including objects hidden or obscured by terrain, fog, and other structures. Next generations of emerging sensors will be capable of generating and communicating large amounts of data. The sensor capability will come from multiple platforms with overlapping sensor coverages and resolutions to include chemical, biological, explosive, and laser among others. These systems will have the communications capabilities to provide real time processing of data. With these capabilities, UAVs paired with explosive detection sensors will be a viable life-saving addition for ground forces in 2030.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**50**	

Disclaimer

Contents

Page

DISCLAIMER ii

LIST OF ILLUSTRATIONS v

PREFACE vi

ABSTRACT vii

PART 1

INTRODUCTION 1

PART 2
Developments in IED Technology 3

PART 3
Commonalities Among IEDs 5

PART 4
Promising Sensor Technologies 9

PART 5
Current Obstacles to Technologies 21
Platform Capabilities and Limitations 22

PART 6
Communications 27

PART 7
Implications 28

CONCLUSIONS..29

APPENDIX A: LIST OF ABBREVIATIONS 35

APPENDIX B: INTERVIEW FRANK PATTON 36

APPENDIX C: INTERVIEW MARK FISHER……………………………………………….37

BIBLIOGRAPHY 41

List of Illustrations

Page

Figure 1. IED Components 5

Figure 2. Conventional Munition IED 6

Figure 3. Vapor Pressure of Common Explosives 8

Figure 4. Sensor Design 10

Figure 5. Trace Detection Technologies……………………………………………………11

Preface

Improvised explosive devices (IEDs) are responsible for approximately 30% of combat casualties in Afghanistan and 50% in Iraq to include both killed and wounded. This paper explores solutions to reduce the threat posed by IEDs to ground forces and noncombatant nationals through the development of explosive detection sensor technologies capable of remotely locating and identifying the presence of IEDs. This paper could not have been written without the generous assistance of Dr. Frank Patton Project Manager, Strategic Technology Office, Defense Advanced Research Project Agency and Dr. Mark Fisher, Senior Scientist at ICx Nomadics Inc.

Abstract

Explosive detection sensor micro unmanned aerial vehicles (UAVs) equipped to identify the presence of improvised explosive devices (IEDs) and communicate their locations to commanders will significantly decrease military and civilian casualties in an unconventional warfare environment of 2030.

The forecasting methods used for this paper are environmental scanning and genius.

The Department of Homeland Security is encouraging research in Low Vapor Pressure Chemical Detection System (LVPCDS) programs to develop, field-test, and transition systems required to effectively detect high explosive residues and toxic low vapor pressure compounds. The LVPCDS program will assist DHS' goals of developing enhancements to existing detection components and systems, developing new components and systems, as well as creating next generation systems. Proposed short range systems will be fully autonomous, portable and able to rapidly detect low vapor pressure chemicals from 3 meters or less without contacting the contaminated surface.

ICx Nomadics Inc and GE have both demonstrated with their differing technologies that TNT can be detected in the vapor phase from a standoff distance of between 1 to 3 meters using sensors with sensitivity in the parts per trillion ranges. In order to detect low vapor pressure agents at the same distance as TNT can be detected currently, sensors may require sensitivity to the parts per quadrillion to quintillion (10.0 E 12- 10.0 E 15) ranges. With this capability, sensors may be able to detect TNT from a standoff distance of 6-9 meters.

A realistic vision of a 20-year future has fielded U.S. forces able to see a complete picture in their normal field of view including objects hidden or obscured by terrain, fog, and other structures. Next generations of emerging sensors will be capable of generating and communicating large amounts of data. The sensor capability will come from multiple platforms with overlapping sensor coverages and resolutions to include chemical, biological, explosive, and laser among others. These systems will have the communications capabilities to provide real time processing of data. With these capabilities, UAVs paired with explosive detection sensors will be a viable life-saving addition for ground forces in 2030.

Part 1

Introduction

Improvised explosive devices (IEDs) pose a serious threat to US forces and the noncombatant nationals inhabiting the CENTCOM Area of Responsibility (AOR). IEDs are responsible for approximately 30% of combat casualties in Afghanistan and 50% of casualties in Iraq (includes killed and wounded).[1] Improvements in the medical treatment of IED casualties such as Self Aid and Buddy Care on the battlefield as well as surgical and aeromedical evacuation advances have reduced the "Died of Wounds Rate" to below 10%. Although previous conflicts rate was closer to 30%[2] (approximately 10-15 thousand people are alive today because of these medical advances), IEDs are still responsible for approximately 7,000 wounded in action "not-returned to duty" injuries as of March 24, 2009[3].

The Joint IED Defeat Organization (JIEDDO) anticipates an increase of IED attacks on soft targets as terrorists conduct asymmetric warfare in an urban environment. Soft targets provide a wide "audience" for U.S. forces and non-combatant national casualties. DARPA Director Tony Tether testified to Congress in 2005 that the key to limiting IEDs was in identifying their source. He stated that part of the problem faced thus far was because the terrorists were able to quickly respond and adapt their strategies to the US' partial solutions.[4] One challenge to readily identifying IEDs is that they can be designed out of any conceivable material, take any desired shape, and be constructed quickly and cheaply. Explosive materials may originate from military sources or from readily available materials.

Triggering methods include using a cell phone, garage door opener, a radio controlled toy, or other simple means. The adaptation of using remote control devices has given the extremist the ability to watch forces and initiate the IED from outside the blast zone.[5] In order to

protect themselves from IED detonation via radio-controlled switching mechanisms, ground forces employ radio frequency jammers. However, if a patrol comes under attack, commanders stop jamming certain frequencies in order to radio for help. During this time when jammers are down, vulnerability is created providing an opportunity for terrorists to detonate a roadside bomb.[6]

The variety of methods used includes emplaced bombs, vehicle born improvised explosive devises (VBIEDs), and suicide bombers. The result is that IEDs are difficult to discriminate visually and the variety of configurations makes finding common characteristics by which to identify them a singular challenge. The Defense Department has established the JIEDDO for the purpose of developing counter IED projects through the Defense Advanced Research Projects Agency (DARPA). To date, much of counter IED has been on increasing the blast resistance of vehicles and on jamming technologies to prevent detonation. There are several predominant counter IED strategies which have emerged from Pentagon-sponsored research: prevent radio-controlled detonation by employing frequency jamming techniques; defeat the impact of IEDs by increasing vehicle safety; improve the treatment of casualties; and improve the capability to detect IEDs. This paper will focus on the latter strategy, with an emphasis on remote detection capabilities

This paper will explore the capabilities and limitations of the most promising sensor designs and provide analysis for the steps necessary to overcome obstacles to their employment in the field. It will evaluate transportation options to bring the sensor into proximity of the IED as well as means to communicate location and description of the IED to commanders. The modern operating environment provides heightened susceptibility to ambush because of urban congestion or by natural rock or vegetative formations in rural locations. IED countermeasures

which can quickly and reliably detect the presence of explosive material from a standoff distance will make great strides towards the safety of combat operations in the modern operating environment.

Part 2

Developments in IED Technology

Terrorists are constantly improving, adapting new technologies into their IED skills. An important component in counter IED strategy includes knowing the terrorist organization, how they employ and execute their mission. The typical terrorist cell consists of six to eight people including a bomb maker and a cameraman.[7] Terrorists record these scenes and distribute them via the internet to highlight the US' vulnerability to attack and galvanize supporters of the terrorists' cause. [8] Extremists are now sending their recruits to engineering schools to learn IED manufacturing skills as well as to control the radio frequency spectrum.[9] In 2003, the sophistication of IEDs found in Iraq evolved from simple suicide attacks to remote-control vehicle born IEDs and daisy- chained IEDs using tripwires.[10] The evolving complexity indicates a specialized skill set within a terrorist network rather than a fragmented, disorganized function. Thus, by removing this specialized function, the terrorist organization loses a critical capability.

Dr Azahari bin Husin held a PhD in statistical modeling from Redding University in England. Instead of choosing a career in academia, he chose a career in making homemade bombs for the Jemmaah Islamiah terror organization. [11] Dr Azahari sometimes used Tupperware™ like products as compartments to prevent the effects of humidity on the explosive materials. He also employed complex wiring systems and modular designs placing detonators

made from television antennas on both ends of the explosives so they would burn faster. [12] Although Dr Azahari is now dead, his advances in bomb making have spread throughout the Philippines, Sri Lanka, Afghanistan and Algeria via person-to-person training, instructional CD-ROMs, technology exchanges, and through remote or vicarious instruction available through the internet.[13]

Ease of information sharing has led to evolutions with both the complexity of the IED and the strategies behind the placement of the IEDs. Terrorists may use decoy devices as bait out in the open to slow or stop convoys in the kill zone of the actual device that is hidden along urban travel routes. Meals, ready-to-eat (MRE) boxes, soda cans, manholes, tunnels burrowed under roads, cement-encased bomb projectiles, and even dead animal carcasses have been used by the terrorists to conceal IEDs. Vehicle borne IEDs (VBIEDs) may be found in any form of vehicle available to include instances of what appeared to be generators, donkey drawn carts, and ambulances used to attempt attacks on Coalition Forces and the New Iraqi Government. VBIEDs have increasingly used larger amounts of explosives ranging anywhere from 45Kg to over 450 Kg. The explosive charges have included mortar rounds, rocket motors, rocket warheads, plastic explosives, and artillery rounds. A growing technique in VBIED attacks in Iraq has involved using multiple vehicles where the lead vehicle acts as a decoy or barrier buster. Once the lead vehicle is stopped, the vehicle containing the IED comes crashing though the checkpoint and into the crowd before detonating; thus resulting in an increase of the casualty ratio.

Part 3

Commonalities among IEDs

All IEDs are a variation of a design consisting of a power source, a switch or triggering device, a compartment, an initiator, and a main charge.[14]

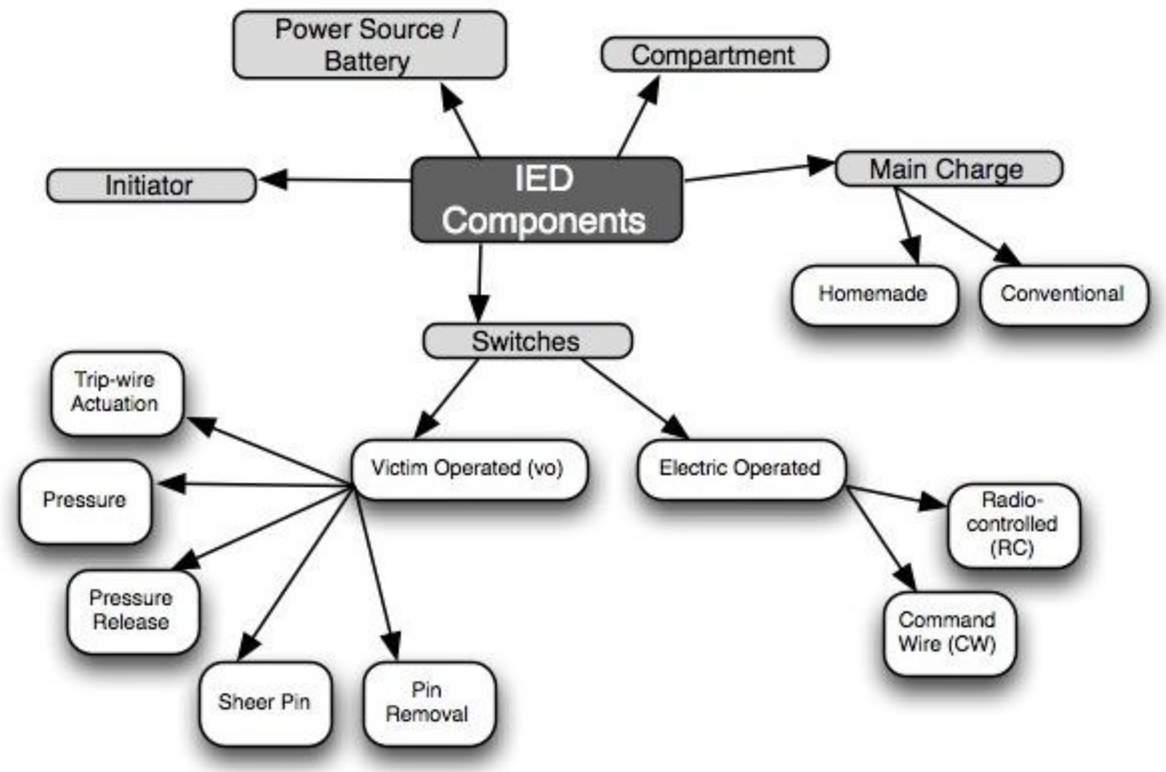

Figure 1 IED Components

Figure 1 depicts the elements found in IEDs. Power sources apply energy to the IED and commonly take the form of a battery. The switch or triggering device is the mechanism by which the IED is initiated. This can take the form of a radio control (RC) device, a command wire (CW) which require a current to pass between two contacts, a timer, or a victim operated (VO) switch. Victim operated switches are based on pressure, pressure release, or trip wire actuation. Improvised firing devices are usually of the shear pin or pin removal type. [15] The

initiator is a small explosive charge used to detonate the larger, main explosive charge and can take many diverse forms. Radio and cell phones are commonly used to initiate IEDs. Speaker wire can be used to connect the explosive device to the hide position. The main charge for IEDs in the Middle East usually takes the form of conventional military munitions which are used in an unconventional manner.[16] The chemical signature emanating from the explosive agents used in IEDs appear to be the critical link unifying IED configurations and providing a basis for a consistent method of detection.[17] Although triggering and compartmentalization mechanisms are advancing, the main charges are not changing. IEDs are easily made with conventional munitions, and the Defense Department estimates that there are 7 million tons of large caliber munitions in Iraq.[18] Because of the unpredictable nature of homemade explosives, terrorists would much rather use readily available sources. Explosives are not comprised of pure chemical elements, but usually contain complex chemical entities to include; synthesis by-products, unreactive synthetic starting materials, or degradation by products. For example, trinitro toluene (TNT) is an explosive material with convenient handling properties whose explosive yield is considered the standard measure of strength for explosive agents.

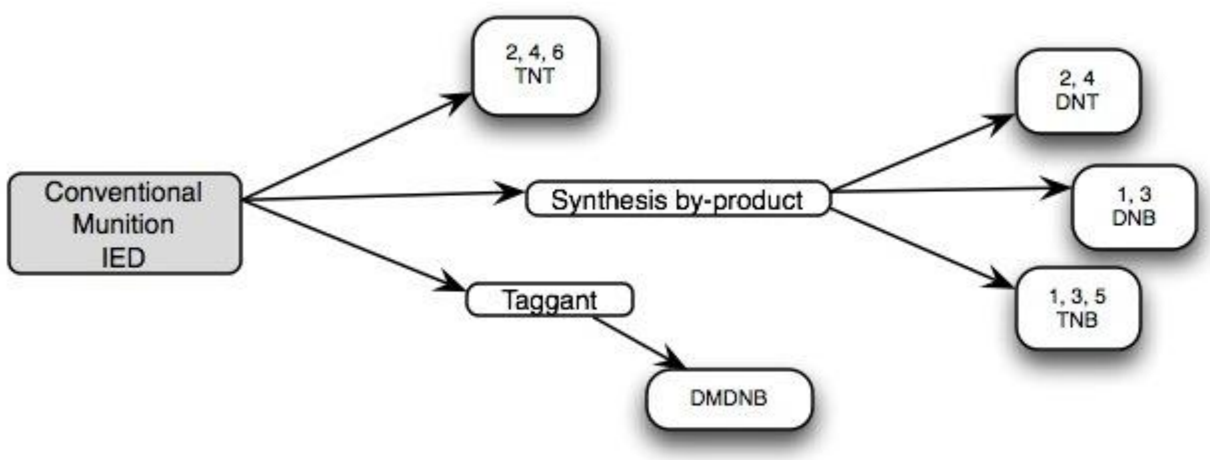

Figure 2 Conventional Munition IED

In Figure 2, an IED formed from conventional munitions may contain more than TNT alone, such as taggant agents and synthesis by-products that are the result of incomplete nitration of toluene. Depending on the synthesis process and how well the explosive was purified, mono and di-substituted nitrotoluenes may be present at levels ranging from trace to a few percent by mass. This is important because both mono and dinitrotoluenes have higher vapor pressures than TNT and may make valuable detection indicators[19]. Any compound found in an explosive that is unique to the explosive, and is always found in the vapor signature regardless of its source or age could be used as a means of detecting the explosive. Taggants are volatile chemicals which are added during the manufacture of chemicals which are found typically only in explosives. This reduces the likelihood of a false positive when taggants are detected. Although various technologies exist to detect untagged explosives, detection taggants help to increase their reliability and their inclusion in explosives is mandatory in many countries, including the US pursuant to the Antiterrorism Act of 1996. DMDNB (2,3-Dimethly-2,2- dinitrobutane) is a taggant that is associated with plastic explosives and is the most commonly used taggant in the US. Detecting taggants is a viable strategy for combating domestic terrorism; however, it should not be relied upon for detecting IEDs in the battle space since terrorists may not be using explosives manufactured under US guidelines.

Military grade (trinitrotoluene) TNT generally contains about 99% of 2,4,6-trinitrotoluene. The most abundant explosive related compounds (ERCs) evolving from military grade TNT is often 2,4-dinitrotoluene (2,4-DNT). DNT is only found in the presence of explosives, thereby, reducing the potential for false positives. Other important components of ERCs are 1,3-dinitrobenzene (1,3-DNB), 1,3,5-trinitrobenzene (TNB), other geometric isomers of DNT and DNB, and 2,4,6-trinitrotoluene (2,4,6-TNT).[20] The vapor pressure of the

compounds making up the explosive determines the maximum concentration of vapor available for detection. In order to detect a chemical signature, the sensor must pass through a vapor plume emanating from the source.[21] Vapor pressure depends on the ambient temperature and explosive type. For high vapor pressure explosives such as NG, EGDN, and TNT, the saturated vapor pressure can be as high as 10 parts per billion, but for explosives such as PETN (found in priming cords and detonators) and RDX (found in plastic explosives) the saturated vapor pressure is as low as 10 parts per trillion, making these explosives very difficult to detect in the vapor phase. It may be possible to detect the higher vapor pressure constituents of the plastic explosives rather than the low vapor pressure explosive chemicals themselves.[22] Although unreliable, current technologies are able to detect NG, EGDN and TNT from standoff distances of 3 meters under controlled conditions. To date, sensor capabilities do not permit PETN or RDX detection from a standoff distance. However, as sensitivity and selectivity grow from 10 parts per trillion to 10 parts per quadrillion, it is logical that sensors would be able to detect both PETN and RDX from distances comparable to today's TNT detection capabilities. (See Figure 3)

	EGDN	NG	TNT	RDX	PETN
Explosives detectable at parts per billion	Available	Available	Available	Available	Available
Explosives detectable at parts per trillion	Available	Available	Available		
Explosives detectable at parts per quadrillion	Future Capability	Future Capability	Future Capability	Future Capability	
Explosives detectable at parts per quintillion	Future Capability	Future Capability	Future Capability	Future Capability	Future Capability

Figure 3 Explosive Detection Capabilities and Requirements
(White row is direct sampling, gray-shaded rows are vapor sampling)

Because terrorists want to use IEDs to produce a localized effect rather than a “mega-bomb”, IEDs can be made with relatively small amounts of explosives. For this reason, sensor technologies need to be capable of reliably detecting small quantities of both high and low pressure explosives if they are going to be viable for counter IED.

Part 4

Promising Sensor Technologies

Approaches that seek to combine multiple sensor technologies, combining their strengths to compensate for unique weaknesses into systems capable of detecting a wider range of threats, show greater potential for success. There are several functional elements that make up all sensors. The stages listed below describe functional stages not physical elements. A single physical piece of hardware may perform more than one step. The primary sensing element first receives energy from the sampled medium and produces an output. The instrument always extracts some energy from the measured medium. Thus, the measured quantity obtained from the sample is always affected by the act of measurement which makes perfect measurement theoretically impossible. Instruments are designed to minimize this effect, but it cannot be completely eliminated.

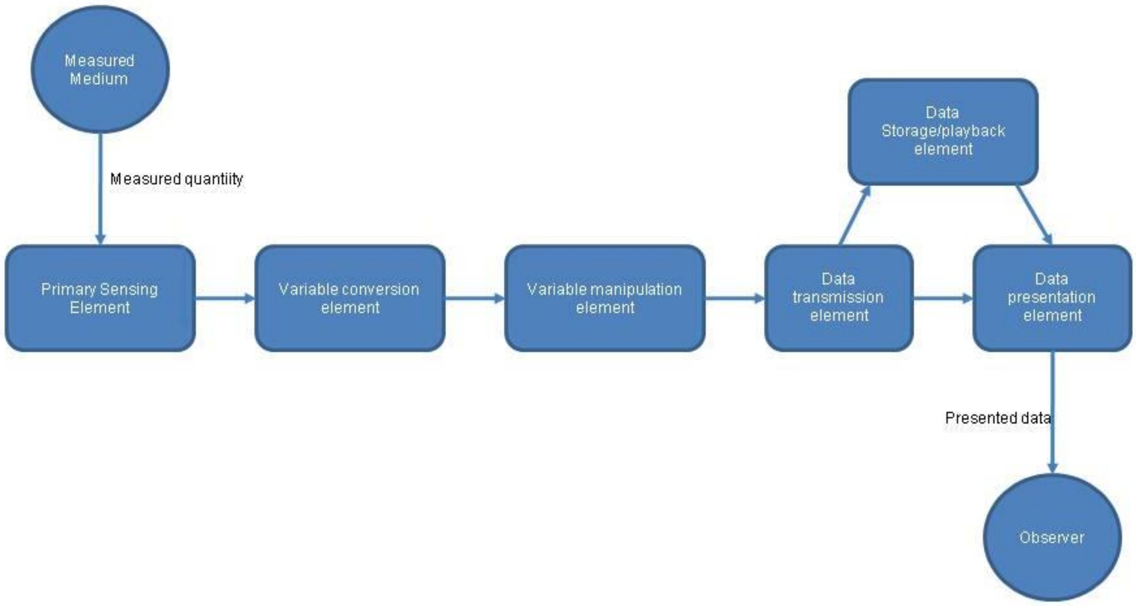

Figure 4 Sensor Design

The output from the primary sensing element is a variable such as displacement or voltage. This output variable must be converted to a variable that is suited for the sensor's specific purpose. The variable conversion element serves this function. If the signal requires that there be a change in its numerical value according to a definite rule while maintaining the physical nature of the variable, then that function is called a variable manipulation element. Data is then transmitted from one function to another by a data-transmission element. Data may then be stored or enabled for presentation to the ultimate observer.[23]

How close the sensor will have to be to the explosive for consistent detection depends on several factors. When vapors of explosives are released into the air, the vapor is rapidly dispersed, lowering the actual concentration of analyte in plumes by as much as 100 to 1000 times[24]. The concentration decreases further as the distance from the explosive device increases, therefore, detection of explosives in the vapor phase requires sensitive detectors and or the use of sample preconcentration methods. How well the explosive is concealed is more important to

sensor sensitivity than the quantity of explosive present. Although not airtight, a car trunk provides a barrier to chemical detection because vapors emanating from the trunk are reduced. Therefore, a 900 kilogram sample of TNT concealed in the trunk of a vehicle is much more difficult to detect than a 700 gram TNT sample placed under the seat of a vehicle where air can move freely. Under conditions controlled for temperature, size of sample, selection of ERC, and placement of the sample, it has been possible to detect explosive vapor approximately 3-4 meters away from the source.

Figure 5 shows current trace explosive detection technologies, including those mechanisms with the potential for standoff detection[25]. Of the below existing technology lines, this paper will forecast about the potential for developing standoff detection capabilities from specific technologies derived from biosensors, electronic and chemical sensors, and optical sensors.

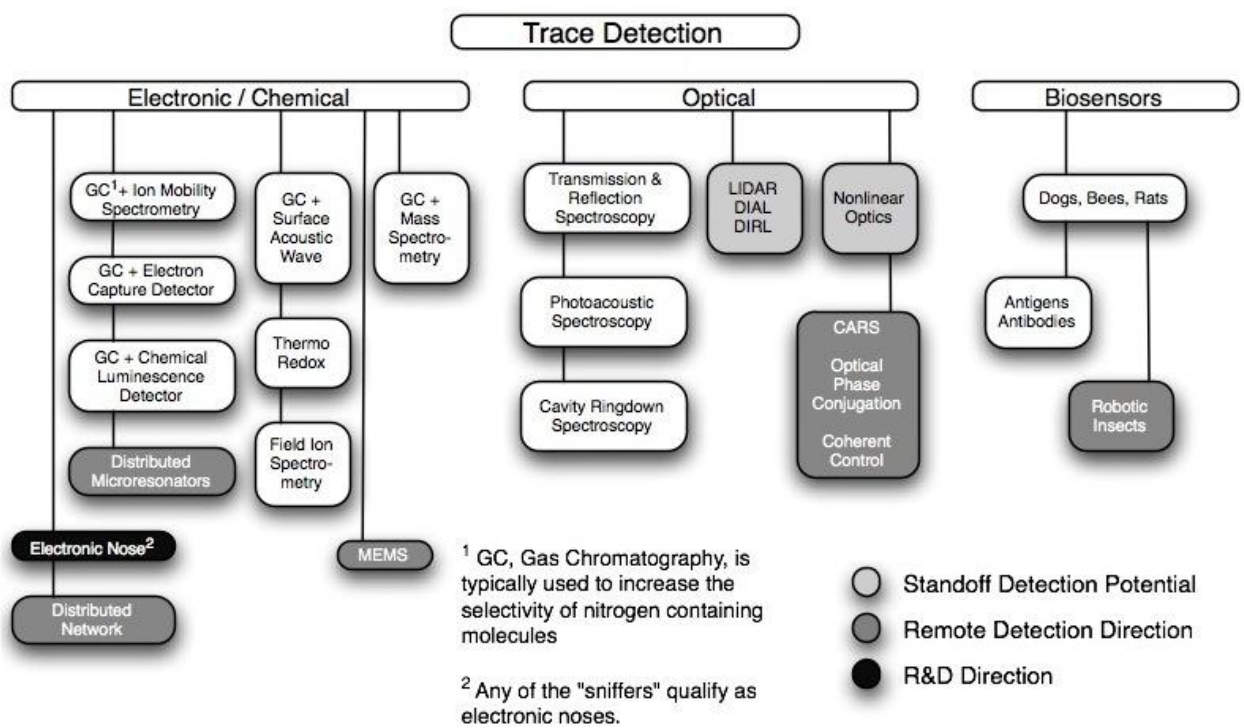

Figure 5 Trace Detection Technologies

Bio mimicry or the development of artificial "noses" as an avenue for detection technologies is based upon the premise that honeybees and dogs have the ability to be trained to be extremely sensitive and selective chemical sensors capable of detecting IEDs.[26] In 1999, Sandia National Laboratories and DARPA began exploring the idea of using honeybees to detect bombs.[27] The bees' highly specialized sense of smell could be trained to associate explosives with nectar. The original plan was to have bee hives located near key checkpoints and have tiny radio transmitters attached to the bees to report where they landed. The problem with this was that bees could not operate at night, in the rain, or in cold weather. Additionally, during testing, the bees became distracted when nectar in was placed in unrelated directions, creating a vulnerability that terrorists could exploit.

The sensitivity of dogs to different chemical components of military grade TNT has been shown to be about 100 parts per trillion or 1nanogram of ERC vapor per liter of air with performance declining in the 200 parts per trillion to 1000 parts per trillion range[28] They have the capacity to detect explosive vapors from 30 centimeters to many meters away depending on concealment, explosive type, and environmental conditions. As sensitive as dogs are to detecting explosives, they must "alert" from within the blast zone. These highly trained assets are by no means disposable. Ultra-sensitive electronic sensors with detection thresholds rivaling canines have the potential to detect IEDs equally well. Trace vapor sensing offers the possibility of standoff detection and the possibility of deployment on small remotely-operated robotic platforms.[29]

Sniffer-based technologies derived from canine inspiration include cantilever based "mechanical noses", High Frequency Quartz Crystal Microbalance (HF-QCM), and fluorescent polymer based sensors. The combination of the chemical binding of molecules in the nose and

the vibration of that particular molecule into a “mechanical nose” provides a very sensitive detective method surpassing canine capabilities.[30] In order to reproduce artificially, scientists from University of Nevada in Reno and Oak Ridge Laboratory in Oak Ridge have developed a miniature cantilever sensor which has two integrated elements, a combined sensor and actuator and an integrated heating element which combined are smaller than an ant’s eye. When the sensor catches explosive vapors, the integrated heater triggers a micro explosion on the sensor surface leading to its ability to detect TNT vapor and to distinguish it from other vapors. TNT is the lowest vapor pressure explosive that can be identified in the vapor phase with a sensor operating in real-time.

The Mini-Nose developed by Scent Detection Technologies Ltd (SDT) mimics a mammalian nose and uses HF- QCM technology. The hand-held product consists of a sampling unit and analyzer and contains an array of sensors and coatings which provide high sensitivity and selectivity for detection and identification of trace chemicals. The coatings are selective to specific molecular families of both explosive and non explosive chemicals. These sensors measure changes in resonating frequency.[31] The Mini-Nose has proven itself reliable when working in dusty, humid, high traffic areas. The Mini-Nose has high utility for airport or check point screening, but does not show promise as a remote detection application because of the necessary for physical contact between the sensor and an object which has been exposed to explosives i.e. clothing or baggage.

Nomadics Inc. introduced the Fido XT sensor that uses a fluorescent polymer based sensor capable of detecting vapors sensitive to parts per quadrillion (PPQ).[32] The total weight for Fido XT sensor and batteries is approximately 3.8 pounds—down from its original 20 lb prototype. In order to address the problem with detecting low vapor pressure chemicals,

Nomadics Inc. has developed a vapor preconcentrator which has been attached to a sensor. The vapor preconcentrator draws a sample of air into a small tube which has been coated with material that has a high affinity for ERCs. Non-explosive components of the sample pass through a filter and out of the tube. The sample in the tube is then heated rapidly and moved to the sensor for analysis. The preconcentrator allows 1000 liters of air to be sampled at the same time as it would take to sample 1 liter of air without the preconcentrator. The likelihood of detecting a contaminate increases with the preconcentrator because the opportunity to collect a portion of contaminated air has increased[33]. With the attached preconcentrator, the Fido XT was able to reproducibly detect the vapor source from a 25 picogram sample of TNT with 60 centimeters between the explosive contaminated source and the sensor. Despite the small distance, it is a benefit over direct sampling which requires physical contact with the contaminated item. The cycle time for the preconcentrator system is approximately 30 seconds including a 10 second sample collection period.[34]

Nomadics Inc. has been able to detect explosive plumes from many meters away with the sensor mounted on robotic vehicles, provided the conditions are right. Successful detection at these distances is currently possible, but not with a high degree of probability. Nomadics Inc. mounted their Fido XT vapor detector on a small, unmanned helicopter platform (the NRI AutoCopter) and attempted to remotely detect explosive agents. The sensor was mounted to a tether and suspended approximately 7 meters below the helicopter in order to remove the sensor from contact with rotor wash. Rotor wash efficiently mixes the vapor plume with clean air, which dilutes the vapor leading to an increase in false negative results. The experiment was conducted with the temperature controlled at 100 degrees Fahrenheit and tested a 5000 kg sample of TNT placed without concealment on the surface of the earth. When the sensor was

placed downwind of the target and it was able to detect the explosive at a distance of a few centimeters to about 1 meter away. When the sensor was mounted directly to the underside of the helicopter, positive detections from a 1 meter distance were possible provided that the helicopter was positioned downwind from the sample such that the rotor wash pulled the vapor plume from the explosive across the detector.[35] The 30 second analysis period is not be rapid enough to provide immediate feedback concerning the specific location of an explosive, however, the sensor would provide information that an explosive device was somewhere in the flight path of the vehicle. The hovering platform is attractive because it enables the sensor to be positioned close to a suspected target and held in position long enough to achieve detection in some cases. This is encouraging for continued research in this area with the idea that greater gains in distance may be attained in the next 20 years.

Electronic/Chemical sensors not based on biomimicry include SERRS (surface enhanced resonance raman spectroscopy) and MEMS (micro electro mechanical systems) and their derivatives. Advanced polymeric coatings show promise in making sensors that are both highly selective and sensitive to parts per trillion. Both the SERRS and MEMS microcantilever based devices will likely benefit from these coating technologies. It is speculated that the coatings will provide real time analysis leading to the accurate identification of multiple CBRNE substances Raman Spectroscopy, a spectroscopic technique used to study vibrational, rotational, and other low frequency modes in a system and relies on inelastic scattering, or Raman scattering, of monochromatic light, usually from a laser. Raman Spectroscopy has been used successfully in forensic and medical laboratories to identify explosives, illicit drugs, polymers, proteins, DNA sequences, and chemical warfare agents.[36] SERRS has resulted in the development of instruments that promise to greatly reduce or eliminate the possibility of false positives or

negatives for explosive and biological threat agents. The sensors are portable (bench top or hand-held capability). Their sensitivity to less than 1 part per billion is not considered sufficient at this time, but there are hopes that these challenges will be surmountable with continued research.[37] SERRS' analysis time of 1-2 minutes makes them slower than optimal for real time detection of explosives, but that too shows promise.

Along with developing more sensitive sensors, there is value in miniaturizing the sensor. A miniaturized sensor mounted on a UAV could be flown into an urban area at low enough levels to the earth to be able to successfully detect the presence of IEDs. Using a top-down manufacturing processes has helped enable micro and nano technologies. These processes include lithography, etching and deposition techniques to sculpt a silicone substrate and then build structures using it. Nonbiological micro-electro mechanical systems (MEMS) provide a way to miniaturize in the micro world.

MEMS are structures, devices, or systems having some parts on the scale of micrometers. One class of MEMS is sensors that transducer some aspect of the world into electronic data. Another class includes mostly actuators, the inverse of sensors, which transducer information into a physical, chemical or biological effects. Miniaturization into the nanometer domain of nanoelectromechanical systems (NEMS) is the gradual development along the trend of miniaturization.[38] Nanotechnology offers possibilities beyond the advantages offered by MEMS and other microsensors. The integration of nanomaterials (microelectronics integrated with micro optics and micromechanics) blurs the distinction between device and system and makes it possible to integrate the different levels to the point that the material essentially is the device and possibly also the system.[39] Miniaturized gas ionization detectors using titania nanotubules have been used successfully in a wireless sensor network as a gas chromatography detector[40]. Sensors

using nanocantilevers have been fabricated by using a focused ion beam (FIB) technique. By forming an array of sensors, they may have sensitivity to detect a single chemical and biological molecule. Fabrication of sensor arrays and devices by parallel processing methods similar to chip fabrication will lead to inexpensive sensors. Sensitivity of these sensors is obtained through the forces that depend on the nature of molecular interactions and the methods used for detections. For biological sensitivity, using DNA-type or polypeptide interactions, highly selective determinations are possible. By comparing the changes in response of an array of different materials exposed to an agent, a characteristic pattern can reveal the agent's identity. Currently, a vibrating cantilever sensor has been able to detect the presence of a single E. Coli bacterium in air with a mass of less than 1 nanogram.[41]

The SnifferSTAR is a half-ounce unit, portable, chemical detection system designed to be mounted on UAVs and detect vapors from nerve gases and blister agents. It combines a nano material for sample collection and concentration with a MEMS based chemical laboratory on a chip sensor. Progress is being made, but challenges include reducing the cost of materials and devices, improving reliability, and packaging the devices into useful products. Because of the size of the technology, it may be possible to put nano-sensors into individual cells permitting measurement of molecular interaction and kinetics on a small scale at very high speed. Operating on half a watt of power, the SnifferSTAR consists of a butter-pat-sized sensor platform on top of a microprocessor board. The airstream is sampled every 20 seconds by the sensors, which register the mass of airborne particles as electronic frequencies and send the signals to the processor; the digital data are transmitted to the UAV or to a ground link, where they are immediately compared against a library of data patterns for many dangerous gases. Other new sensor technologies include inexpensive microarrays of DNA sensors on a chip that

can detect multiple pathogens, such as anthrax and smallpox; acoustic sensors that use sound waves to determine the chemical composition of materials in closed containers; and handheld radiation detectors, now commercially produced and deployed in homeland security activities.[42]

Ion Mobility Spectrometers (IMS) instruments, their derivatives, and the Mission Adaptable Chemical Sensor (MACS) are classified as optical sensors. IMS instruments measure the migration of gas phase ions through a homogenous electric field, measuring up to 40 different substrates reliably in less than 30 seconds. However, the spectrometers do require calibration changes in between classes of chemicals. Although calibration only takes 5-10 minutes, it may not currently allow for the flexibility needed in battlefield operations. [43] When the potential for multiple classes of components exists, the manufacturers recommend that there be dedicated IMS units that are each calibrated for separate classes of chemicals. IMS units are routinely used at security checkpoints for screening and detection of illicit drugs, chemicals, and explosive agents and are the most commonly used detection technology. Instrument sizes range from desk top as used in airports to hand held models. Components of IMS devices used for performing particle analysis tend to be more rugged than those used for vapor analysis. There are several manufacturers of various IMS products working towards homeland security projects.

IMS is limited in that components of IMS devices used for performing vapor analysis do not tend to be rugged and the unit does not function well detecting vapor samples when environmental conditions exceed 18°C. The low vapor pressure of nitro aromatic explosives means that they are almost impossible to detect in cooler environments. Environmental contaminants, dirt, grease, water, can be detrimental to the sensors and may cause false positive results. These products have high utility for explosive detection in indoor locations. Battlefield

utility will likely be reserved for detecting chemical warfare agents which are more easily detected in the vapor phase.

Ion Trap Mobility Spectrometry (ITMS) is a derivation of IMS. Like IMS, ITMS separates ionized vapors and then measures the mobility of the ions in an electric field. The gaseous samples enter an ionization chamber where an ionizing source emits low-energy beta particles resulting in ion formation in the gaseous phase. ITMS differs in that ions reach equilibrium in a field-free region and are then pulsed into the tube where an electric field guides the ions to the collector. Without the shutter grid found in the IMS system, the ITMS permits a greater number of ions to enter the drift tube resulting in detection at a lower level of sampling and a more rapid result.

GE's Mobile Trace is a hand-held IMS device with an operating temperature of 0-50 ° C and permits simultaneous detection of a broad range of explosives and narcotics. The particulate sensors are reliable to parts per billion (PPB) which is within normal limits for analyzing particle swipe samples and the vapor sensors are sensitive to parts per trillion (PPT). Samples measured may be solid or gas, collected either by a sniffing device for vapors or a "swipe" method of solid particulate matter. A sniffing device is used to draw vapors through a nozzle directly into the system for analysis. Typical sampling objects include cargo containers, luggage, and car trunks. Analysis times for the both vapor and particle detection are approximately 8 seconds.

The REMPI (resonance enhanced multi-photon ionization) technique is a derivative of IMS combining the principles of optical spectroscopy and mass spectrometry to provide a two-dimensional detection scheme that yields a high degree of chemical sensitivity and selectivity. REMPI can detect TNT and other high pressure explosive vapors in the parts per trillion range at near ambient conditions and allows real-time analysis with a standoff distance of

about 3 meters. REMPI is limited in its utility as a remote sensing application in that it cannot detect explosive vapors from PETN, HMX, AN, and RDX at ambient conditions and must use direct particle sampling for these compounds, but very effective in close range sensing. [44]

LIBS (laser induced breakdown spectroscopy) is also a derivative of IMS and is a highly specific and sensitive spectroscopic method that provides detection at the molecular element level. It is capable of identifying up to seven different elements concurrently while measuring their proportions within a 1 nano gram sample[45]. It is able to complete its analysis of multiple elements in less than 1 second which makes it the most rapid product currently available.

The physical components of the instrument are small and capable of identifying aerosolized agents remotely. When presented with a sample, LIBS analyzes and forms a unique chemical finger print. LIBS works by comparing the “fingerprint” against a known chemical reference. This means that once a sample is analyzed, it has to be cross referenced against chemical libraries of data. Therefore, in order for the sensor to be used on a UAV, it will need to have data software loaded on the sensor, or it will need the capability of transmit instantaneously to another source that has the data loaded. LIBS has shown great utility in detecting biological or chemical warfare agents. When tested for landmines, it has been able to differentiate between plastic and metal casings with 80% accuracy in controlled experiments.[46] LIBS is being considered as a secondary level of inspection at vehicle identification stations when one is searching for specific hazardous materials. The current Army prototype is field portable and can operate for 2 hrs on a lithium battery. JIEDDO has projects currently under development with the goal to extend the range for LIBS to detect explosives from a 30 meter standoff distance.[47]

The MACS cannot detect chemical threat "signatures" from any distance and requires an atmospheric sample to ingest before it can provide identification of the analytes. Spectral

measurements have been conducted at high altitude where pressure is greatly reduced, and the atmospheric constituents then show up as sharp, identifiable emissions. In the MACS this is handled by simply pumping down on the samples using a sorbent to concentrate the analytes of interest, then liberate the gases from the sorbent with a pulse of heat, and the spectra become sharp and easily identifiable at the reduced pressure[48]. According to Dr Frank Patton, Strategic Technology Program Manager at DARPA, there is no instrument at present that can detect and identify the chemical components of a threat at any distance consistently and accurately enough to be operationally useful. DARPA has invested in techniques in which vendors claim to detect chemical threats remotely with spectral identification in the visible or infrared, or even to stimulate such signatures using a laser or some other method, but the instruments delivered have not proven reliable.

Part 5

Current Obstacles to technology

IEDs stored with other munitions tend to give off a higher concentration of explosive vapors than those belonging to the IED alone. If the IED's structural material is permeable to explosives vapors—which is common with most plastics, diffusion of explosive vapors through the structural materials to the outside should be sufficient for detection for several decades. Non-permeable materials like metals tend to have cracks, seams, and seals that allow escape of explosive materials from the interior of the item.[49]

Plume filaments contain concentrations of explosive that are slightly less than those found at the source and can persist a significant distance from the source which is what permits standoff detection. However, the greater the distance from the source the filaments are sampled, the smaller the concentration of explosive in the filaments. The number of plume filaments per

unit volume of air also decreases as the distance from the source increases. This means that as the distance between the source and the point of sampling increase, the larger the volume of air that must be processed in order to ensure that the plume filaments have been sampled.[50]

Atmospheric pressure has the effect of "broadening" all of the emissions expected from the molecules of the threat species, such that the "lines" overlap each other resulting in an undifferentiated broad spectrum that offers no information of value.[51] The viable distance between the explosive and the vapor sensor is currently at best measured in centimeters, making it necessary for platforms carrying the sensor to remain inside the blast zone. Other concerns with this distance are that it is difficult to “sweep” a specified area of land, rather current technology requires approaching suspected objects for confirmation.

The variety of current vapor analyzing technologies take between 1 to 30 seconds to complete a sample. The speed of sample analysis becomes less of an issue if the sensor is mounted on a platform with loitering capabilities. Being able to loiter on one position at a time would allow greater concentration of analyte to be processed increasing the likelihood of correct identification, and would allow more correct recording of the explosive’s location. The size of the sensor does not appear to be a significant problem for product development in the future. As nanotechnology improves battery and power source miniaturizations, the size of the entire sensor will decrease such that it will be applicable regardless of desired platform.

Platform Capabilities and Limitations

In testing, one knows which piles of rocks or vehicles conceal IEDs and which do not. This means that researchers have time to direct the robot until it is positioned sufficiently to record a sample. There is currently a 2-3 second time lag in transmission of video and audio signals to the operator making it difficult to know the exact position of the robot in real time.[52]

On the battlefield the presence of IEDs are unknown and time is a limited commodity. For these reasons, having an sensor that can scan a large surface area remotely and quickly would be a significant asset. With these issues in mind, robotic platforms as well as hovering, micro, mini, and swarming UAV technologies show potentil for future use in combat carrying sensors within detectable range of IEDs.

The iRobot Corporation has been awarded $16.58 million for delivery of 100 packbot explosive detection robots carrying the ICx FIDO XT payload for the military in Iraq. The packbot with the ICx FIDO XT sensor can detect explosive vapors when its sensor is placed within a range of a few meters to several centimeters from IEDs (sensitivity depends on ambient temperature and wind conditions) and then destroy or disrupt them using its built-in water cannon. The human operator can remain at a safe distance away from the explosive.[53] Problems found with robotics include the ability of the robot to articulate itself so that the sensor can be near the item being sampled without actually running into it.

The utility of a UAV for ground forces in urban combat has much to do with its survivability. If the UAV is designed to fly low, below 6 meters from the ground (the height of most power lines), then it can easily be identified and becomes an open target. In theory, the UAV should have the capacity for speed to reduce its opportunity for being targeted by the enemy, or it needs to be hardened to reduce its susceptibility to rifle fire. However, because it is flying low through congested areas, the paradox is that the UAV needs to fly slowly so the operator can safely maneuver it around a multitude of obstacles. If the product is designed to fly between heights of 7-30 meters, the necessity for speed is reduced, because the UAV becomes a less noticeable target.

The Army is currently employing 15 centimeter Class I hovering UAVs in urban combat operations in Iraq for their ability to “perch” on top of buildings and “see” around corners as ground forces move through heavily congested corridors. Because explosive detection sensors currently require varying times to analyze sampled volumes of air, platforms with the capability to hover or perch, have particular applicability. The controller flies the UAV with close proximity to the platoon/squadron. This allows them to better protect the UAV from enemy fire.

Micro unmanned aerial vehicles (MUAVs), generally refers to 15 centimeter or smaller flying platforms.   Micro UAVs current capabilities include flying at 10 meters/second for 5 kilometers. However, as the analysis time necessary for sensors decreases, platform flying speed will be able to increase. It has been proposed that future systems could fly nearly 1185 kilometers per hour for 1000 kilometers or endure for tens of hours.[54] Commercially available off the shelf autopilot systems weigh from 120-180 grams. Since the payload for smaller UAVs is less than 7 grams, this severely limits payload capacity available for autopilot, power, and sensors. Current technology constrains MUAV capabilities because the size of the power source limits flying time. The maximum weight available for payload (Wm) is achieved when battery weight is reduced to zero and the maximum powered flight time is achieved when payload weight (Wp) is zero, where in the payload is replaced by batteries. [55]

Mini UAVs have wingspans ranging from 15 centimeters to 3 meters and have a flying speed of 20-50 miles/hour and include The Air Force’s BAT-CAM (Battlefield Air Target Camera) and the Dragon Eye. The BAT-CAM tested by Special Operations Forces at Hurlburt Field, FL is a mini UAV weighing less than 370 grams and has a 61 centimeter wingspan. The BAT-CAM is being tested for special operations, battle damage information, and other potential missions. Researchers hope to miniaturize the BAT-CAM into a “pocket version” with a 23

centimeter wingspan in the future.[56] BAT-CAM researchers are planning to adapt missions to include urban operations and bio-chemical sensing as well as over the hill reconnaissance and rescue missions. The Dragon Eye is a mini UAV with a 114 centimeter wingspan weighing about 680 grams and appears to be a useful platform for carrying the HAZMATCAD chemical agent sensor. This sensor detects nerve, blister, blood and choking agents with a fast response mode of 20 seconds and a sensitive mode of 120 seconds. And can log data for 8 hours. The instrument weighs 198 grams without batteries. The Dragon Eye is reported to be able to fly the HAZMATCAD sensor for 54 minutes or about 56 kilometers. This translates to being able to send the Dragon Eye on a 16 kilometer mission and have it turn around and fly back home. If a small camera were added, there would be little additional weight or power needed. [57] The impact would be real time in situ testing for biological and chemical agents as well as visual imagery. Real time video transmission from UAVs is currently limited to a few miles with the power drawing about 1 watt. One could, in theory, extend the video range by connecting the UAV to a "mother ship" to relay the communication further. Next generation versions of platforms developing bio-chemical sensing and urban operations will translate into tangible gains with explosive sensing.

Converting insect behaviors into algorithms combined with the computational power of modern computing may lead to the production of inexpensive swarming micro- UAVs. A swarm is a collection of a large number of relatively simple components such as bees in a hive. Each individual unit has limited capabilities, but as a group, they can perform large-scale missions. The swarm, not the individual, is the important entity because of the greater combined capabilities and the ability to function many times over the lifespan of the individual.

Swarming permits large numbers of UAVs to be flown simultaneously. Translating insect algorithms into a reliable artificial intelligence will permit minimal human controller input. [58]

In nature, pheromones are chemical markers that determine the level of attractiveness or unattractiveness an object has. The ant highway around an anthill is one example. Using "digital pheromones" similar to the way that ants mark their territory, a UAV can detect how much of an individual terrain has been covered by itself and other UAVs and autonomously change their course towards unexplored areas

The ability to fly low in swarming formation has potential effectiveness for explosive detection assuming that the swarming UAVs are considered disposable; therefore, do not need to meet survivability standards discussed previously. The idea is to make develop small, inexpensive (around $2,500) units which could be deployed together in the hundreds. This way, if individual units are destroyed or fail, there would be redundancy ensuring mission continuance. In order to use swarming UAVs and/or micro UAVs as a reasonable platform, significant miniaturization of sensors and power sources will be necessary. Fortunately nanotechnology driven power sources appear to be developing in viable directions. Invoking gliding technologies in the Micro UAV design will extend the duration of flying time. Sensor, materials, power, and autopilot technologies to include global positioning system navigation (GPS) continue to miniaturize such that they should be viable components on swarming and micro platforms.

The tight integration of sensing, signal-processing, computation, and communication functions that become possible because of parallel mass fabrication of microsystems increases performance and reduce unit costs. Sensor systems-on-a-chip will be used in the future for the cost-effective production of swarms on microplatforms.

One challenge is that swarming UAVs will place a premium on bandwidth on the battlefield. The communication network will include many sources of large amounts of data, multiple nodes attempting to access information, redundant communication channels to ensure connectivity as well as multiple protocols to ensure authenticity. Bandwidth management and maintaining secure communications are vital to mission success. To manage bandwidth and provide accurate sensor information, the UAV must process as much information as possible before transmitting it. Size limitations and processing demand of micro aircraft make this a significant challenge.

For UAVs to perform in the modern environment as platforms for explosive sensors, the sensor needs to develop significant sensitivity such that they are able to reliably detect explosive chemical signatures from a distance that provides survivability and maneuver for the UAV. If research proves incapable of delivering sensors with such sensitivities, then UAVs need to become plentiful and inexpensive such that they could be considered disposable enough to use in a low-flying swarming platform.

Part 6

Communication

The Air Force Research Laboratory is working on the AngelFire ISR system which is a persistent sensor and the data distributions system in near real time. It is the sensor on the aircraft and the data distribution system on the ground. While still largely classified, some details about its capabilities are available. AngelFire consists of wide area electro-optic and infrared staring sensors able to provide scalable city size coverage. It is capable of providing day or night persistent real time video surveillance of an area at 1 frame/second relayed to commanders with a 5-10 second delay. AngelFire is being tested as an embedded system on five King Air A-90

aircraft capable of conducting a 1-3 kilometer radius orbit. Its software consists of a GUI (Graphical User Interface) similar to "Google Earth" and maintains 7 days worth of data for playback analysis.[59] Researchers speculate that it would be technically possible to use the AngelFire system as a mother ship to relay information from micro UAVs to commanders in real time.

Part 7

Implications

The Department of Homeland Security is encouraging research in Low Vapor Pressure Chemical Detection System (LVPCDS) programs to develop, field-test, and transition systems required to effectively detect high explosive residues and toxic low vapor pressure compounds. The LVPCDS program will assist DHS' goals of innovating enhancements to existing detection components and systems, developing new components and systems, as well as creating next generation systems. Proposed short range systems will be fully autonomous, portable and able to rapidly detect low vapor pressure chemicals from 3 meters or less without contacting the contaminated surface.[60]

Scientists at DARPA believe there may be a way to accurately identify the chemical components of a threat at a distance by making the portion of atmosphere around the object suspected of concealing an IED register a very low pressure. This would cause the explosive signature emanating from the object to be amplified, thereby allowing accurate sampling of the object's infrared emissions at a distance. According to Dr Patton, he is working with DARPA to fund this direction of research, to the extent of setting up the components in a laboratory and proving the concept.[61] Further elaboration on this concept quickly moves into classified areas.

Nomadics Inc and GE have both demonstrated with their differing technologies that TNT can be detected in the vapor phase from a standoff distance of between 1 to 3 meters using sensors with sensitivity in the parts per trillion range. In order to detect low vapor pressure agents within the same range as it is currently possible to detect TNT, it is likely that sensors would require sensitivity to the parts per quadrillion to quintillion (1.0 E 15- 1.0 E 18) range. If sensors can be developed with sensitivity within the quadrillion to quintillion range, not only will low vapor pressure agents be able to be identified within 1-3 meters, but, TNT might then be identifiable ranging between 6-9 meters. With these capabilities, UAVs paired with explosive detection sensors would be a viable life-saving addition for ground forces in 2030.

Part 8

Conclusion

IEDs pose a serious threat to US forces and the noncombatant nationals during modern warfare. To date, factors improving survivability largely center around advancements in trauma medicine, aero medical evacuation processes, and up armor technologies. Further research into IED detection capabilities would provide great gains in survivability. One challenge to identifying IEDs is that they can be designed from readily available materials as well as conventional munitions, take any desired shape, and be constructed quickly and cheaply. Because of the variety possible among IEDs, finding a common element is key to developing detection technologies. Any compound found in an explosive that is unique to the explosive, and is always found in the vapor signature regardless of its source or age could be used as a means of detecting the explosive.

Explosives contain many chemical entities in low concentrations to include: synthesis by-products; unreactive synthetic starting materials; or degradation by products as well as the parent explosive compound. The vapor pressure of the compounds making up the explosive determines the maximum concentration of vapor available for detection. In order to detect a chemical signature, detection sensors must pass through a vapor plume emanating from the source. The higher the vapor pressure of the explosive used, the greater the concentration of analyte in the plumes. How well the explosive is concealed effects how well the vapor is able to leak into the atmosphere for detection. When vapors of explosives are released into the air, the vapor is rapidly dispersed, lowering the actual concentration of analyte in plumes by as much as 100 to 1000 times[62] Atmospheric pressure has the effect of "broadening" all of the emissions one could expect to see from the molecules of the threat species, such that the "lines" overlap each other resulting in an undifferentiated broad spectrum that contains no valuable information.[63]

The viable distance between the explosive and the vapor sensor is currently at best measured in centimeters, making it necessary for platforms carrying the sensor to remain inside the blast zone. At this limited distance, it is difficult to “sweep” a specified area of land, rather current technology requires approaching suspected objects for confirmation. In testing, one knows which piles of rocks or which vehicles conceal IEDs and which do not. On the battlefield the presence of IEDs are unknown and time is a limited commodity. The modern operating environment provides heightened susceptibility to ambush because of urban congestion or by natural rock or vegetative formations in rural locations. IED countermeasures which can quickly and reliably detect the presence of explosive material from a standoff distance will make great strides towards the safety of combat operations and for noncombatant nationals occupying areas in conflict.

Advances in micronization, power, speed, and flying distances will benefit hovering, micro, mini, and swarming UAVs platforms for incorporation with sensors for remote IED detection and improve means to communicate location and description of the IED to commanders. DHS sponsored Low Vapor Pressure Chemical Detection Systems programs will work to develop, field-test, and transition systems required to effectively detect high explosive residues and toxic low vapor pressure compounds. Next generation systems will be fully autonomous, portable and able to rapidly detect low vapor pressure chemicals from 3 meters or less without contacting the contaminated surface. Current technologies using sensors with sensitivities in the parts per trillion ranges demonstrate under controlled conditions that TNT can be detected in the vapor phase from a standoff distance of between 1 to 3 meters. Estimating from current capabilities, next generation systems detecting low vapor pressure agents would require sensors with sensitivity to the parts per quadrillion to quintillion (10.0 E 15- 10.0 E 18) range in order to detect them at the same distance as one can currently detect TNT. Sensors developed with sensitivity to the quadrillion to quintillion range, not only will detect low vapor pressure agents within 1-3 meters, but, TNT might then be identifiable between 6-9 meters, an appropriate range for combat use with mini UAV platforms. If research proves incapable of delivering sensors with such sensitivities, then UAVs need to become plentiful and inexpensive such that they could be considered disposable for use in low-flying swarming platforms.

A realistic vision of a 20-year future has fielded U.S. forces able to see a complete picture in their normal field of view including objects hidden or obscured by terrain, fog, and other structures. Next generations of emerging sensors will be capable of generating and communicating large amounts of data. Sensors capable of distinguishing the location of explosives will evolve such that detection of IEDs from distances of six meter or greater will be

possible. Sensor capability will come from multiple platforms with overlapping sensor coverages and resolutions to include chemical, biological, explosive, and laser among others. These systems will have the communications capabilities to provide real time processing of data and the ability to provide information to ground commanders to aid in prosecuting the ground campaign.[64] With these capabilities, UAVs paired with explosive detection sensors would be a viable life-saving addition for ground forces in 2030.

Notes

[1] Wilson, *IEDs in Iraq and Afghanistan: Effects and Countermeasures*
[2] Gerhart, *Out-of-Hospital Combat Casualty Care in the Current War in Iraq*
[3] Defenselink Casualty Report 2009 03 19.xls ; www.defenselink.mil/news/casualty.pdf
[4] Ibid
[5] http://defense-update.com/features/du-3-04/IED.htm
[6] IBID
[7] Wilson, *IEDs in Iraq and Afghanistan: Effects and Countermeasures*
[8] Stapleton-Gray, *IED Detection*
[9] Magnuson, *Hidden Enemies: Adaptive Foe Thwarts Counter-IED Efforts*, 22
[10] McFate, *Iraq: The Social Context of IEDs*, 37
[11] Magnuson, *Weapons of Choice) Bomb Making Skills Spread Globally*, 26
[12] IBID
[13] Cragin, Chalk Daly, Jackson, *Sharing the Dragon's Teeth*
[14] Smith, Coderre, *The continuing War against Improvised Explosive Device*
[15] IBID
[16] http://www.defense.gov.au/publications/IED_fact_sheet.pdf
[17] *Explosive Chemical Signatur-Based Detection of IEDs*
[18] IBID
[19] Fisher, *Applications of Sensors Utilizing Amplifying Flourescent Polymers for Ultra-Trace Level Detection of Explosives*

Notes

[20] Jenkins, Walsh, Miyares, *Analysis of Explosives-Related Chemical Signatures in Soil Samples Collected Near Buried Land Mines*

[21] Fisher, Mark interview

[22] Patton, Frank interview

[23] Doebelin, *Measurement Systems*, 11

[24] *Existing and Potential Standoff Techniques,* , 86

[25] *Existing and Potential Standoff Techniques*, 73

[26] Fisher, *Explosive Chemical Signature-Based Detection of IEDs*

[27] Schechter, *Sensing*, 32/33

[28] Goth, McLean, Trevelyan, *How Do Dogs Detect Landmines*

[29] Fisher, *Explosive Chemical Signature-Based Detection of IEDs*

[30] Auner, *Mobile Robot Enabled Detection of Explosives and Biological Agents*

[31] Brinn, *Sniffing Out Trouble*

[32] Riley, *Sensor Feasibility Report, Air Force Research Laborator* , 4

[33] Fisher, Mark Interview

[34] Fisher, *Explosive Chemical Signature-Based Detection of IEDs*

[35] Fisher, *Explosive Chemical Signature-Based Detection of IEDs*

[36] Riley, *Sensor Feasibility Report*

[37] *Existing and Potential Standoff Techniques,* 90

[38] Foster, *Nanotechnology, Science, Innovation, and Opportunity* ,45

[39] Ibid.,45

[40] Ibid.,171

[41] *Implications of Emerging Micro and Nano Technologies*, 91

[42] *Foundations for National Securities, Technologies at Work on the Front Line*

[43] Foster, *Nanotechnology, Science, Innovation, and Opportunity* ,3

[44] Sausa, Cabalo, *A Laser-Based Explosives Sensor,*

[45] Wilson, *IEDs in Iraq and Afghanistan: Effects and Countermeasures*

[46] Foster, *Nanotechnology, Science, Innovation, and Opportunity*, 5

[47] Wilson, *IEDs in Iraq and Afghanistan: Effects and Countermeasures*

[48] Patton, Frank Interview

[49] Fisher, *Applications of Sensors Utilizing Amplifying Flourescent Polymers for Ultra-Trace Level Detection of Explosives*

[50] Fisher,*Applications of Sensors Utilizing Amplifying Flourescent Polymers for Ultra-Trace Level Detection of Explosives*

[51] Patton, Frank Interview

[52] Fisher, *Applications of Sensors Utilizing Amplifying Flourescent Polymers for Ultra-Trace Level Detection of Explosives*

[53] Roosevelt, *iRobot Awarded $16.58 Million for iRobot PackBot with New Bomb-Sniffing Payload*

[54] *Implications of Emerging Micro- and Nanotechnologies*

[55] Coffey, Montgomery, *The Emergence of Mini UAVs for Military Applications*

[56] Kessner, *Air Force Testing BAT-CAM Micro UAV for SOF/BDI Applications* ,1

[57] Coffey, Montgomery, *The Emergence of Mini UAVs for Military Applications*

[58] Huber, *Gathering Swarm*, 32/33

[59] AngelFire Overview

Notes

[60] *Low Vapor Pressure Chemicals Detection Systems Program*
[61] Patten, Frank, Interview
[62] *Existing and Potential Standoff Techniques*, 86
[63] Patton, Frank Interview
[64] *Tactics and Technology for 21st Centrury Military Superiority*, 21

Appendix A

ABBREVIATIONS

ACN Acetonitrile
ADNTs Aminodinitrotoluenes
2-ADNT 2-amino-4,6-dinitrotoluene
4-ADNT 4-amino-2,6-dinitrotoluene
2-ANT 2-amino-4-nitrotoluene
4-ANT 4-amino-2-nitrotoluene
CRREL Cold Regions Research and Engineering Laboratory
DARPA Defense Advanced Research Projects Agency
3,5-DNA 3,5-dinitroaniline
1,3-DNB 1,3-dinitrobenzene
DMDNB 2,3-Dimethly-2,2- dinitrobutane
2,4-DNT 2,4-dinitrotoluene
EL Environmental Laboratory
ERC Explosives-related chemical (TNT, DNT, DNB, ADNTS, TNB)
ERDC Engineer Research and Development Center
GC-ECD Gas chromatography-electron capture detection
HMX 1,3,5,7-octahydro-1,3,5,7-tetranitrotetrazocine
3-NA 3-nitroaniline
PMA-1A Plastic-cased Yugoslavian antipersonnel land mine
PMA-2 Plastic-cased Yugoslavian antipersonnel land mine
QR Quadrapole resonance
RDX 1,3,5-hexahydro-1,3,5-trinitro-1,3,5-triazine
RP-HPLC-UV Reversed-phase high performance liquid chromatography with ultraviolet detection
SARM Standard analytical reference materials
SPME Solid phase microextraction
TKN Total Kjeldahl nitrogen
TMA-5 Plastic-cased Yugoslavian antitank land mine
TMM-1 Metal-cased Yugoslavian antitank land mine
TNB 1,3,5-trinitrobenzene
TNT Trinitrotoluene
2,4,6-TNT 2,4,6-trinitrotoluene
TOC Total organic carbon
Type 72 Plastic-cased Chinese antitank land mine

Appendix B

Inteview: Frank Patten; DARPA

Maj. Guill,

The MACS sensor cannot detect chemical threat "signatures" at any distance - it must have an atmospheric sample to ingest before it can provide identification of the analytes.

Moreover, there is no instrument at present that can detect and identify - accurately - the chemical analytes (constituents) of a threat at any distance, even a few meters. I wish there were such a sensor, and I am trying to develop such an instrument. You may be aware of techniques in which vendors claim to detect chemical threats remotely with spectral identification in the visible or infrared, or even to stimulate such signatures using a laser or some other method, but I can tell you that DARPA has invested in some of these programs and they have not delivered an instrument that is anywhere near reliable.

The problem is this: atmospheric pressure has the effect of "broadening" all of the emissions we could expect to see from the molecules of the threat species, so that the "lines" overlap each other to the point that all you get is an undifferentiated broad spectrum that has no information at all. Spectral measurements have been conducted at high altitude where pressure is greatly reduced, and the atmospheric constituents then show up as sharp, identifiable emissions.

In the MACS sensor this is handled by simply pumping down on the samples we take (usually we use a "sorbent" to concentrate the analytes of interest) - then liberate the gases from the sorbent with a pulse of heat, and the spectra become sharp and easily identifiable at the reduced pressure.

I am very interested in the problem you mention, and there may be a way to accurately identify the chemical components of a threat at a distance; all you have to do is make the portion of atmosphere (say, around the car containing an IED) think it has a very low pressure, and sample its infrared emissions at a distance. I am not kidding, that this is a viable approach; I may be able to convince my management that we should fund this idea, to the extent of setting up the components in a laboratory and proving the concept. However, I don't think it will be ready to try out any time soon in a war zone, I am very sorry to say; but it will be needed even if we leave from Iraq.

Appendix C

Inteview: Mark Fisher; Chief Scientist Icx Nomadics Inc.

How close the sensor has to get to a target depends largely on environmental conditions and the rate of release of explosive signature from the target. Some targets are difficult to detect even from as little as a centimeter away, but we have been able to detect others from close to 100 meters away when conditions are favorable (high ambient temps and a prevailing wind of 5 to 10 mph, and a target in which there was a significant quantity of HE that was not concealed well). High temps drive up the vapor pressure of the explosive, which increases (in general) the rate of release of explosive vapor from the target. A prevailing wind helps because it makes it easier to position the Packbot downwind of the device. And of course, the more poorly the explosive is concealed the better the access to explosive signature. In general, the closer you are to the target the better the chances of detection, but when conditions are favorable you can get significant standoff. When the sensor is deployed on the Packbot, the CONOP does not generally require contact with the device, which is unadvisable for a variety of reasons. We have been able to detect vapor inside a car when explosives are concealed in the passenger compartment, and also when explosives are concealed in the trunk. Again, success depends on a number of the same variables already described.

ICx Nomadics is in fact located in Stillwater. We were acquired by ICx Technologies a little over two years ago, but our operation remains in Stillwater. Our corporate headquarters are in DC, and Nomadics has branch offices in Oklahoma City and Boston. Stillwater is a nice area. If you are ever in the area, feel free to visit.

We actually had a small project with Tinker several years ago. I was not involved in the project, but if memory serves it was to develop a monitoring system for chromium in groundwater.

Preconcentrators process large volumes of sample (air in this case), and extract (filter) target substances from the air. The substances extracted are then released from the filter and re-introduced into a smaller volume of air and analyzed by the detector. Because the mass of analyte is taken from a large volume of air and re-introduced into a smaller volume of air, this in theory should increase the concentration of analyte in the sample.

There is a major caveat to this, however. Many naively assume that if a preconcentrator processes 1000 liters of air that the sample delivered to the detector will contain 1000 times more analyte than if 1 liter of air is sampled. This would be true if the entire 1000 liters of air is uniformly (homogeneously) contaminated with the target analyte. In practice, this is almost never the case. More likely, only a small portion of the 1000 liters sampled would contain target analyte, so the actual concentration enhancement may be very small. Hence, sensitive detectors are still required.

In our experience, the major benefit of using preconcentrators is that you can process a larger volume of air in the same period of time than without a preconcentrator. Hence, you are more likely to detect the target because you increase the chances of collecting a portion of air that is contaminated. You are literally looking for the proverbial 'needle in a haystack', and a preconcentrator enables you to more quickly process the entire haystack.

Vapor plumes emanating from an explosive device can be visualized as similar to cigarette smoke. As the smoke drifts away from the cigarette, the plume becomes more and more filamentous in nature as it disperses. You can see small tendrils of smoke dispersed in air that is largely free from smoke. Even if you sample within the plume, all the air is clearly not contaminated uniformly. If you sample outside the plume, the air will contain nothing. If my sensor only allows me to sample a small portion of the air in the room, I may get lucky and detect the device if I happen to sample from the plume. If I can use a preconcentrator and sample all the air in the room, my chances of detection are good.

I am attaching a paper on this subject that I wrote a few years ago. It may be helpful, especially from page 5 on.

The production version of our sensor does not use a preconcentrator, but we have active R&D efforts to develop these for the sensor and for other sampling applications, such as the one mentioned in my earlier e-mail.
You are correct in assuming that most trace detectors require a general idea of where the target is. They are most suited to confirmation that a target is an explosive device than finding the devices. The problem is not so much that a trace detector can't do a search, but that it takes forever to do a search (in general).

We have worked in the past on area reduction techniques for explosives detection that are intended to identify areas in which explosives may be present, as opposed to identifying the exact location of the explosive in an area. Once an area is identified as suspect, other methods are used to pinpoint the location of the device. The methods essentially sample large volumes of air and extract explosive vapor from the sample stream. The extracted sample is then analyzed by a detector or a dog.
In the canine world this method is known as MEDDS (MECHEM Explosive and Drug Detection System), RASCO (Remote Air Sampling for Canine Olfaction), or REST (Remote Explosive Scent Tracing) depending on who you talk to. It has been used with some success for area reduction of suspected minefields, and more recently has been evaluated by the Brits and French for screening air cargo. We will hopefully soon be under contract with TSWG to begin similar work. I can tell you more about this method if you are interested. The method is approached with

suspicion by some, but others swear that it works. I have seen it work in some circumstances - the trick is getting it to work consistently, which from what I have seen is one of the major challenges with the method. Hopefully within a year we will have much more experience with the method.

The issue with trace detectors being used for general area searches is getting the detector in the vapor plume emanating from a target. If the detector happens to pass through the plume, it may be possible to track the plume to source. If you never intersect the plume, the device will not be detected. The vapor signatures are very hetereogeneous, so detection can be very sporadic. Further, most military explosives have insufficient vapor pressure to be detected in this manner with trace detectors. We have demonstrated detection from some distance away from a source with our detector for TNT, but not RDX or PETN-based explosives. I know of no other trace detector than can do this. It is a real challenge.
There are many factors that will impact how close the sensor will have to be to the explosive to consistently detect it. I assume since you plan to deploy the sensor on a MUAV that you primarily are interested in detection of explosive vapor. The vapor pressure of the compounds making up the explosive determines the maximum concentration of vapor available for detection. The vapor pressure of these compounds depends on the ambient temperature and explosive type. For high vapor pressure explosives such as NG, EGDN, and TATP, the concentration can be quite high, but for explosives such as PETN and RDX the vapor pressure is very low, making these explosives very difficult to detect in the vapor phase unless your sensor detects some of the more volatile constituents of these explosives (usually plastic explosive formulations) such as DMNB (a taggant). TNT is really the lowest vapor pressure explosive you can realistically hope to detect in the vapor phase with a sensor operating in real-time. You may be able to detect higher vapor pressure constituents of plastic explosives, but not the explosive compound (i.e., RDX, PETN) itself.

Another important factor is how well the explosive is concealed. This is usually a more important factor for detection than the quantity of explosive present. A ton of well-concealed explosive in the trunk of a vehicle may be much more difficult to detect than a 1.5 pound TNT demo block under the seat of a vehicle. This factor alone will greatly impact the distance from which an explosive device can be detected.

Not surprisingly, the closer a detector is placed to a source of explosive, the greater the chance of detection. That being said, it is under some conditions possible to detect explosive vapor a significant distance away from the source. A good bomb dog can do this from feet to many meters away depending on concealment, explosive type, and environmental conditions. On a hot day with some wind to direct the plume away from the source in a well-defined manner, dogs have been reported to detect explosive vapor from a surprising distance. We have also been able to detect explosive plumes from many meters away with the sensor mounted on robotic vehicles, provided the conditions are right.
Unfortunately, this is not the norm for our sensors. And, contrary to popular myth, it is also not the norm for dogs. It CAN be done, but not with a high degree of probability.

We have mounted our Fido vapor detector on a small, unmanned helicopter platform (the NRI AutoCopter) and attempted to do what you are interested in. We were somewhat successful in detection of TNT vapor with this system, but I must define the conditions under which we were able to do this. First, the target was 10 pounds of TNT demo blocks piled on the ground, and the ambient temperature was close to 100 degrees. This would constitute an easy target. We deployed the sensor in several ways. The first configuration mounted the sensor to a tether, which suspended the sensor approximately 20 feet below the copter to get it out of the rotor wash. The rotor wash efficiently mixes the vapor plume with clean air, which tends to dilute the vapor, making it more difficult to detect. When the sensor was suspended from the tether and placed downwind of the target, under the conditions mentioned it was possible to detect the explosive when the sensor was anywhere from a few inches to a few feet away. We also mounted the sensor directly to the underside of the copter. When deployed in this configuration, by properly positioning the copter so that the rotor wash pulled the vapor plume from the explosive across the detector, we were able to get detections from about a meter above the explosive.
Positioning of the copter relative to the device was critical in detecting the device, but when it was in the 'right' position it was possible to detect this relatively easy target from about a meter away.
Depending on your CONOPS, this may or may not be useful.

There are possibly some tricks you could use to improve detection, such as vapor preconcentration, but you will loose the real-time detection capability and only be able to say that an explosive device was somewhere in the flight path of the vehicle. This approach is also problematic in that most of the time the vehicle is flying it will likely not be in the explosive plume, so most of what is sampled would be clean air, not contaminated with explosive. Hence, you would still need a very sensitive detector.

Further, if the vehicle is moving rapidly, the response time of the detector will have to be very rapid. This is why the copter platform was attractive. It enabled the sensor to be positioned close to a suspected target and held in position long enough to achieve detection in some cases.

This would also likely require some sensor development, since most of the detectors that may be capable of doing what you are asking are too large and heavy to be deployed on a MUAV. Our detector currently weighs about 3 pounds, which is small, but still likely too large to put on some MUAVs.

I suspect this is not what you hoped to hear. This is a very difficult problem. I would be happy to discuss this further if you have more questions. We also have a report documenting the testing with the copter. If you would like a copy, I will check with the customer to see if he is willing to release a copy. I suspect it would not be a problem. I can also put you in contact with the engineer on the project if you would like more detail. I was not involved in the project, so I was relaying info I got from him. Let me know if I can be of further assistance.

Bibliography

AngelFire Overview, Air Force Research Laboratory, 3 Nov 08
Auner, Gregory. *Mobile Robot Enabled Detection of Explosives and Biological Agents*. Wayne State University, SSIM Program, Nov 2006
Baum, Carl E. *Detection and Identification of Visually Obscured Targets*.Philadelphia, PA, Taylor & Francis, c1999
Brinn, David. "Sniffing Out Trouble."*The Jerusalem Post*, Sept 7, 2007
Coffey, Timothy and Montgomery, John A. *The Emergence of Mini UAVs for Military Applications.* Defense
Cragin,Kim, Chalk, Peter, Daly, Sarah, Jackson, Brian, *Sharing the Dragon's Teeth, Terrorist Groups and the Exchange of New Technologies*. Rand Corporation. 2007
Horizons, No. 22, December 2002. Pg 8 http://www.ndu.edu/inss/DefHor/DH22/DH22.pdf
Cosofret, Bogdan, Gittins, Christopher, and Marinelli, William. "Visualization and tomogrphic analysis of chmical vapor plumes via LWIR imagin Fabry-Perot spectrometry". *Society of Photo-Optical Instrumentation Engineers*, 2004.
Doebelin, Ernest O, *Measurement Systems*, Library of Congress Cataloging in Publication Data, 1983, McGraw Hill
Explosive Chemical Signatur-Based Detection of IEDs. Final Report. 31 Dec 2004
Fisher, Mark, "Applications of Sensors Utilizing Amplifying Flourescent Polymers for Ultra-Trace Level Detection of Explosives" ICx Nomadics, Inc.1024 S Innovation Way, Stillwater, OK, USA 74074
Fisher, Mark. *Explosive Chemical Signature-Based Detection of IEDs*. Final Technical Report, Office of Naval Research, Dec 2004
Foster, Lynn, *Nanotechnology, Science, Innovation, and Opportunity*, Prentice Hall, C 2006 Pearson Education
Foundations for National Securities. *Technologies at Work on the Front Line*. Supplement to the President's FY 2004 Budget
Gerhart, R.T. "Out-of-Hospital Combat Casualty Care in the Current War in Iraq.*" Annals of Emergency Medicine*, May 2009
Goth, Ann, McLean, Ian, and Trevelyan, James. *How Do Dogs Detect Landmines*. a Review of Research Results, Geneva International Centre for Humanitarian Demining (GICHD**),** Department of Mechanical Engineering, University of Western Australia
Huber, Mark."Gathering Swarm."*C4ISR*. Apr 2007 pg 32/33
IEDs a Weapon's Profile; http://defense-update.com/features/du-3-04/IED.htm
Implications of Emerging Micro- and Nanotechnologies. Air Force Science and Technology Board, National Research Council of the National Academies, The National Academies Press, Washington, 2002
Kessner,B.C, "Air Force Testing BAT-CAM Micro UAV for SOF/BDI Applications*"*. *Defense Daily*, Potomac, Sept 2003, Vol 219, Iss. 61 pg 1

Low Vapor Pressure Chemicals Detection Systems Program. Dept of Homeland Security, Synopsis of Broad Agency Announcement 04-10
Magnuson, Stew. "Weapons of Choice Bomb Making Skills Spread Globally." *National Defense*, June 2007,
McFate, Montgomery, Iraq: The Social Context of IEDs, Military Review, Fort Leavenworth: May/June 2005 vol 85 pg 37
Riley, Larry. *Sensor Feasibility Report; Survey of the Capabilities and Limitations of Chemical Biological , Radiological, Nuclear and Explosive (CBRNE) Sensor Technologies Relevant to Vehicle Inspection Systems*. Air Force Research Laboratory, Oct 2007
Rieth, Michael, *Nano-Engineering in Science and Technology : An Introduction to the World of Nano-Design*, New Jersey : World Scientific, c2003.
Roosevelt, Ann." iRobot Awarded $16.58 Million for iRobot PackBot with New Bomb-Sniffing Payload". *Defense Daily*, Vol 233 No 19, Jan 31 2007
Smith, Irene, and Coderre, Michael. "The continuing War against Improvised Explosive Devices an Overview of the Joint IED Defeat Organization". *The WSTIAC Quarterly*, Vol 8 Num 2
Sausa, Rosario. *A Laser-Based Explosives Sensor.*U.S. Army Research Laboratory, Nov 2006
Schechter,Erik. "Sensing". *C4ISR*, July 2007 pg 32/33
Stapleton-Gray." IED Detection- Long-Range Sensor Solution to the Top Terrorist Threat." *C4ISR*, May 2007
Tactics and Technology for 21st Centrury Military Superiority. Vol 1, Final Report, Oct 1996, pg 21
Thomas F. Jenkins, Marianne E. Walsh, and Paul H. Miyares, August 2000 edited by Jessica A. Kopczynski, Thomas A. Ranney, Vivian George, Judith C. Pennington, and Thomas E. Berry, Jr. *Analysis of Explosives-Related Chemical Signatures in Soil Samples Collected Near Buried Land Mines* US Army Corps of Engineers¨Engineer Research and Development Center, Aug 2000
Wilson, Clay. *IEDs in Iraq and Afghanistan: Effects and Countermeasures*. CRS Report for Congress, 25 Sept 2006

http://www.defense.gov.au/publications/IED_fact_sheet.pdf
http:// www.defenselink.mil/news/casualty.pdf
http://www.mdatechnology.net/techprofile.aspx?id=270